King Abdulaziz University
Mechanical Engineering Department

MEP365

Thermal Measurements

Introduction

2022

Contents

Daily use of measurements & control

1-Length [in making drawings, in reporting the area of a land]
2-Weight [Human being, food, materials, etc]
3-Temperature [indoor and outdoor, human]
4-Humidity
5-Blood pressure
6-Tire pressure
7-Petrol (gasoline) for a car in liters
8-Car speed

Daily use of measurements & control

1-Room temperature control (or a thermostat) . The controller receives a signal from the temperature sensor and compare it with the set point temperature and acts accordingly.

2-Cruise control in a car [to maintain a fixed car speed]

In-order to measure we need a sensor. This sensor will measure the physical variable and produce an output

Human senses

1-Touch (Rough & smooth) ١–اللمس

2-Sound ٢–الصوت

3-Color ٣–اللون

4-Smell ٤–الرائحة

5-Taste ٥–الطعم

Stages for measuring a physical variable (measurement system)

1-Sensor-Transducer stage

2-Signal conditioning stage

3-Output stage

4-Feedback stage

Stages for measuring a physical variable (measurement system)

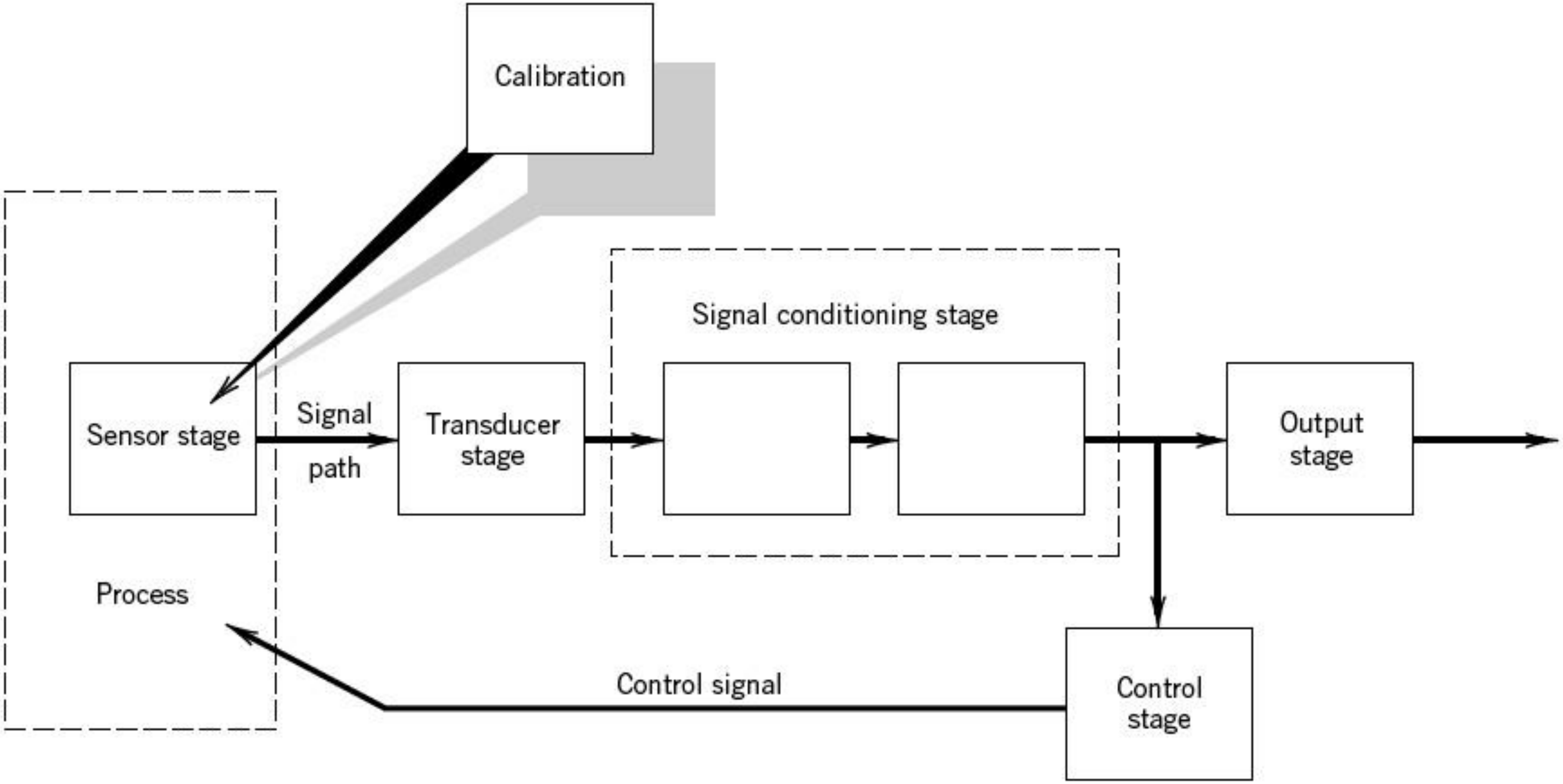

Figure 1.1 Components of a general measurement system.

Stages for measuring a physical variable (measurement system)

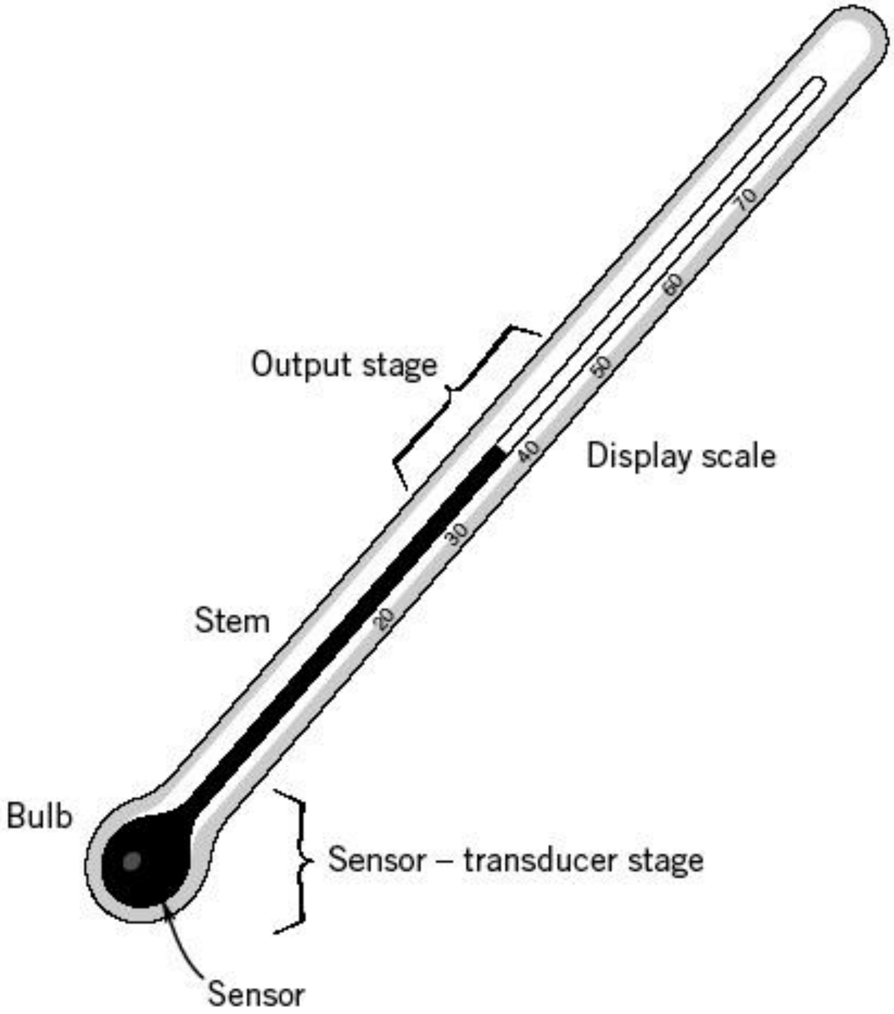

Figure 1.2 Components of bulb thermometer equivalent to sensor, transducer, and output stages.

Stages for measuring a physical variable

1- Sensor transducer stage: sense the variable

Sensor: Is a physical element that uses natural phenomenon to sense the variable

Thermometer Example: Thermal expansion of mercury in a typical thermometer. The bulb is the sensor

Transducer: converts the sensed information into a detectable signal form which might be electrical, mechanical, optical, etc

Thermometer example: Transform the thermal expansion into mechanical displacement in the tube

Some times the word transducer is used to mean both the sensor and the transducer and even signal conditioning

Stages for measuring a physical variable

2-Signal conditioning stage

Optional stage. Basically to modify the signal

-Increase the magnitude of the signal (amplification)

-Removing some portion of the signal (Filtering)

-Providing linkage between the transducer and out put stage: for example converting a translational displacement of a sensor into rotational of a pointer

The diameter of the thermometer capillary relative to the bulb volume determine how far up the stem the liquid moves with increasing temperature.

Stages for measuring a physical variable

3-Output stage

Produce an indication of the value measured.
Examples: Dials, recorders, computer disk

4-Feedback control stage

A controller that interpret the measured signal and make a decision. The decision results in changing the sensed variable. The controller usually compare the difference between the set-point and the measured value.

A house hold Thermostat: is a simple measurement system with controller

Experimental Test plan

Example:

How you plan for measuring the fuel consumption of your car?

Measure fuel consumed and distance travel, then get mileage i.e. (miles per liter)

What variables to be measured?

May be to consider also Distance travel, Road condition, weather condition, driver, etc

How the data will be used?

Steps for measurement test plan

1-Parameter design plan

Test objectives and identification of variables:

Questions: What is the objective of the measurement?, What question am I trying to answer?, What has to be measures?, What **variables** will affect my results

2-System and tolerance design plan

Selection of measurement technique, equipment, and test procedure based on some pre-conceived tolerance error.

Questions: How will I do the measurement and how good do the results have to be?

3-Data reduction design plan

Plan a head on how to analyze, present and use the anticipated data.

Questions: How will I interpret the resulting data? How will I use the data to answer my question?

Identifying variables

Independent

Variables

Dependent

Independent variables: Two variable are independent if changing one has no effect on the other.

Dependent variable: changing one variable changes the other

$y=f(x_1, x_2, x_3)$

x_1, x_2, x_3 are independent variables

y is the dependent variable

control variable: can be held constant or at prescribed condition during the measurements

Identifying variables

variables

→ **discrete**, such as the outcome of throwing a die, or an operator on a machine

→ **continuous**, such as temperature or pressure readout [The value can be for example for T to be between 20 and 30 °C]

extraneous variables: variables that not or can not be controlled during measurement, but affect the measured variable

extraneous variables could cause noise or drift (interference)

Example: measuring the boiling point of water in three days. Pressure (extraneous variable) is not kept constant (no control)

Effect of extraneous variables

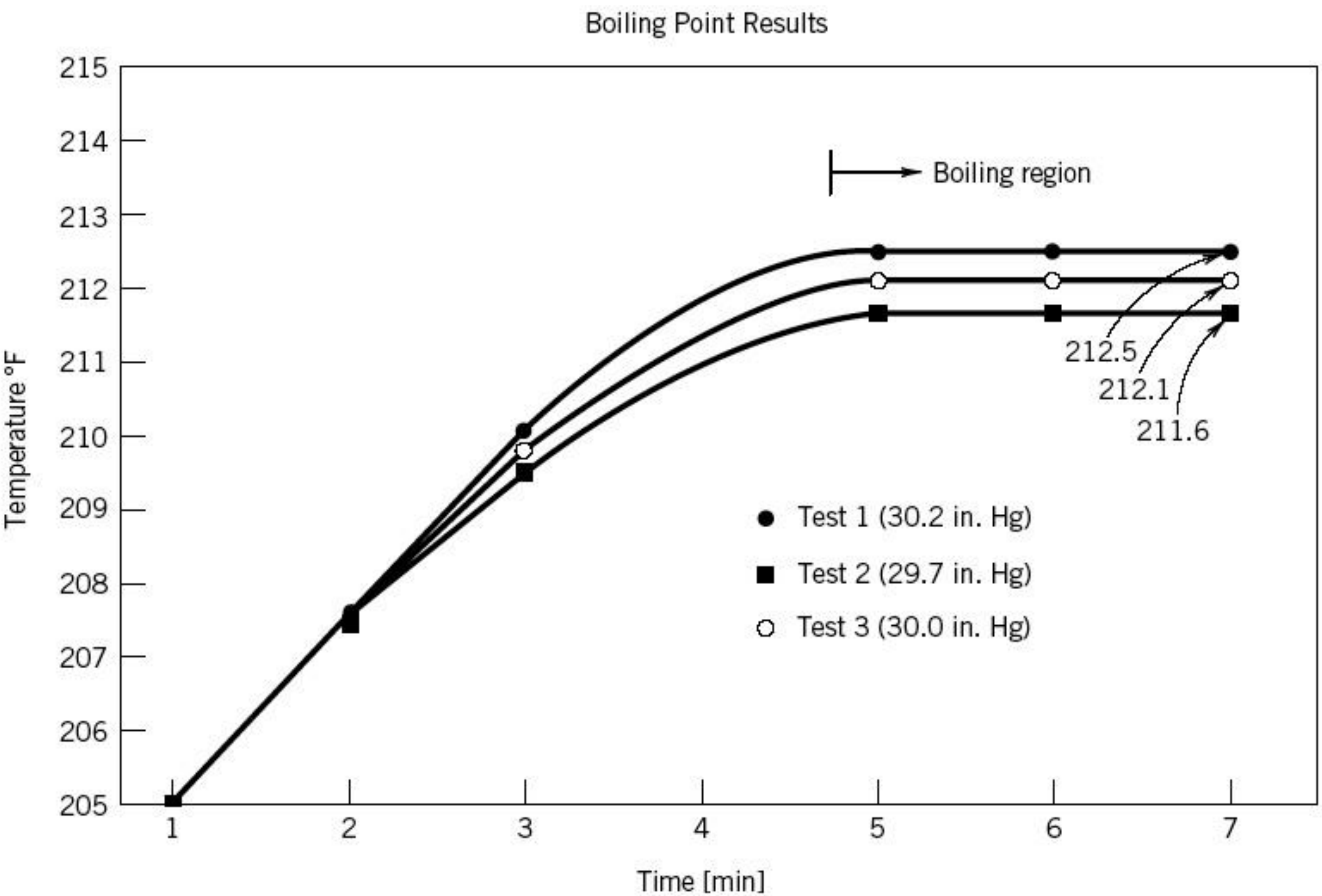

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Figure 1.3 Results of a boiling point test for water.

Parameters

parameter= a functional relation between variables such as $c_1=Q/nd^3$.

Can be found from similarity and dimensional analysis.

control parameter: It has an effect on the behavior of the measured variable.

A parameter is completely controlled if it can be kept constant during the measurement.

Noise and interference

Extraneous variables: variables that are not or can not be controlled. They may cause noise and/or interference on the measured variable

Noise: Random variation of the measured signal due to the variation of extraneous variable.

Examples: Incomplete control of the variables. Normal random variation in environmental condition. Thermal noise (Johnson noise)

Interference: Undesirable deterministic trend on the measured variable.

Examples: Sinusoidal wave superimposed onto a measured signal path. Local AC power line, Fluorescent lights, Electromagnetic interference (EMI)

Noise and interference

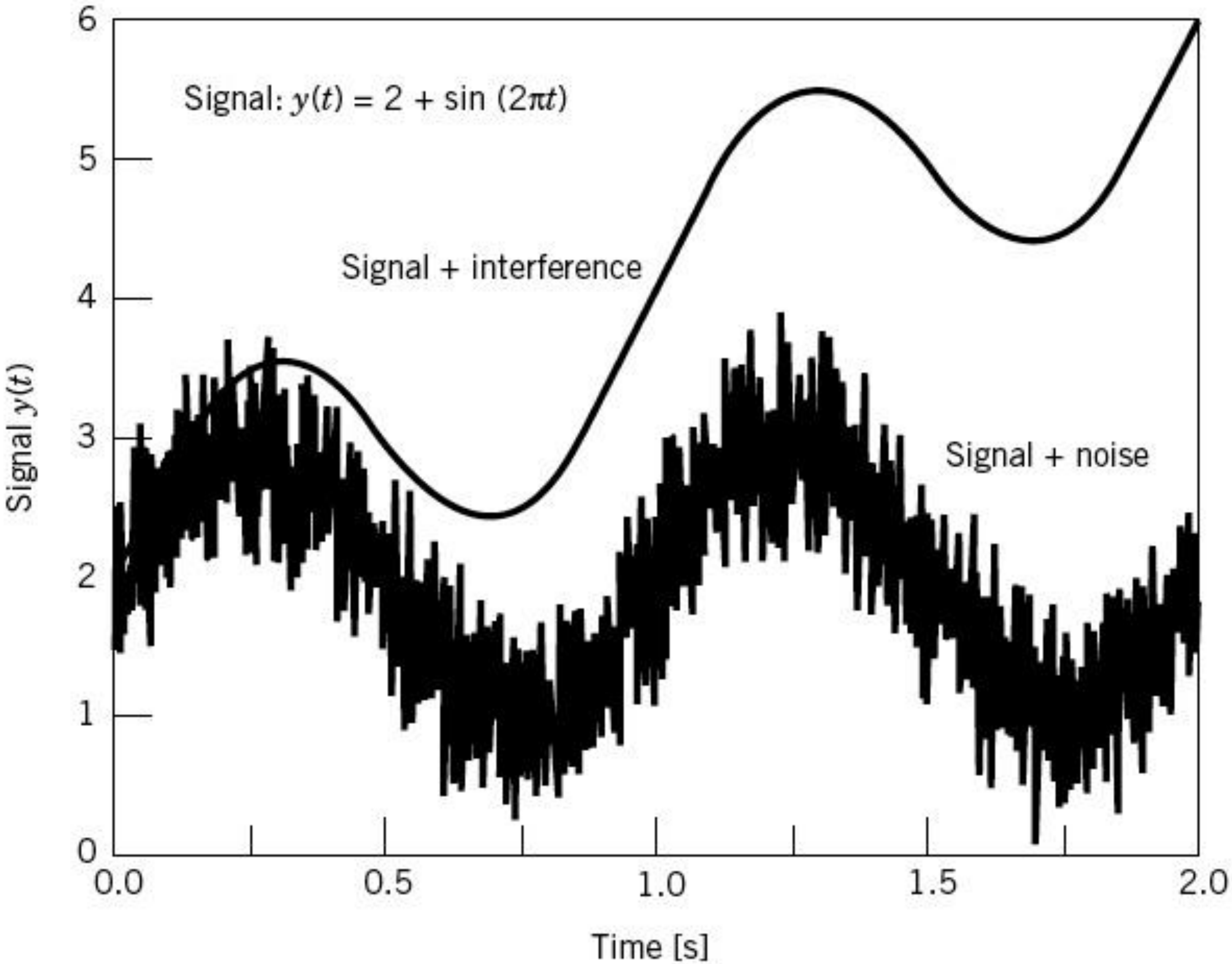


Figure 1.4 Effects of noise and interference superimposed on the signal $y(t) = 2 + \sin 2\pi t$.

Random tests

An important goal is to break the interference trend. This may increase the scattering of the data but it can be handled with statistics (Ch.4)

Randomization method are available to minimize or eliminate interference

Random tests

A Random test is defined by a measurement matrix that sets a random order in the value of the independent variable applied

For example: Road type in our car mileage example as **extraneous variable** can be eliminated by experimenting the car in highways and inside the city.

Random test: Example

For the example of measuring the fuel consumption for a car:

Extraneous variables:

Route, driver, road conditions, weather conditions

Random tests: do the testing with different driver, different road conditions, etc…

Example 1.1

Pressure calibrator

Determine dependent, independent and extraneous variables

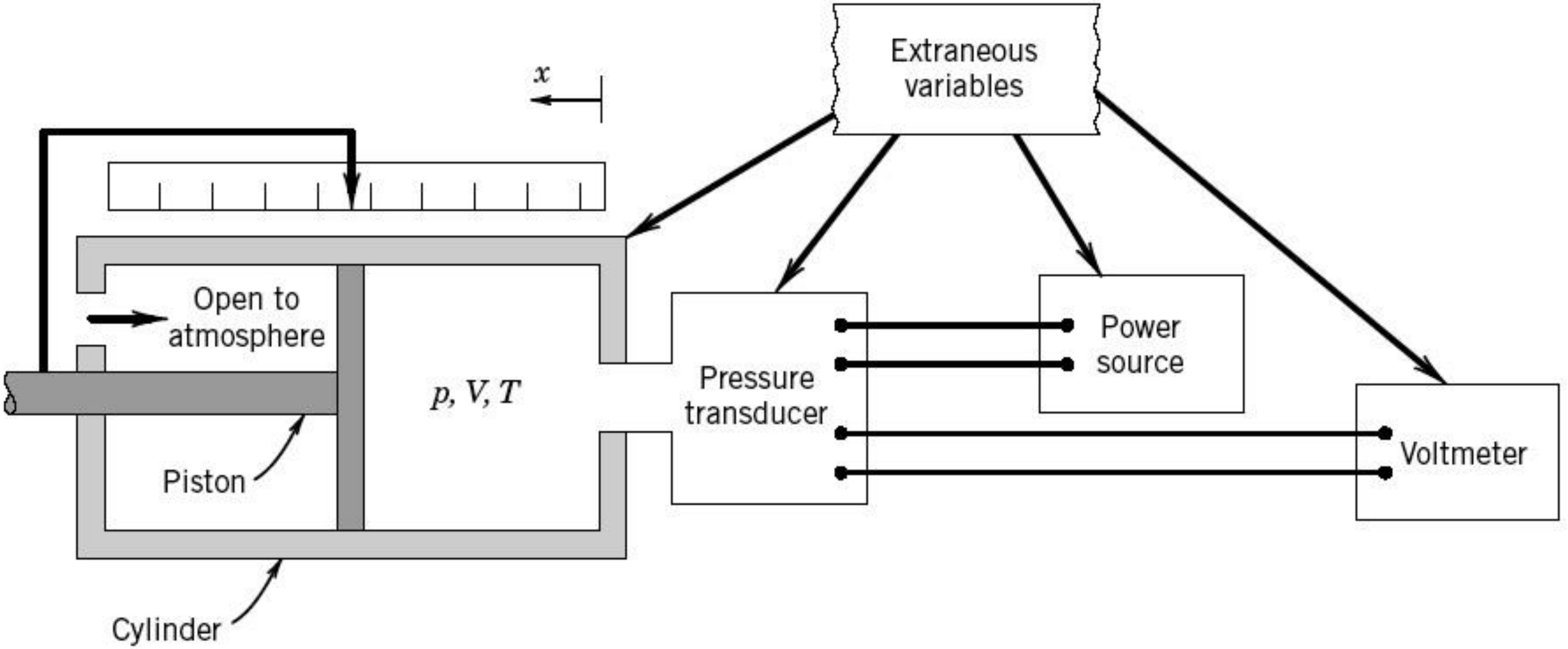


Figure 1.5 Pressure calibration system.

Control parameter PV/T=const

Example 1.1 continue

Control parameter: PV/T=constant

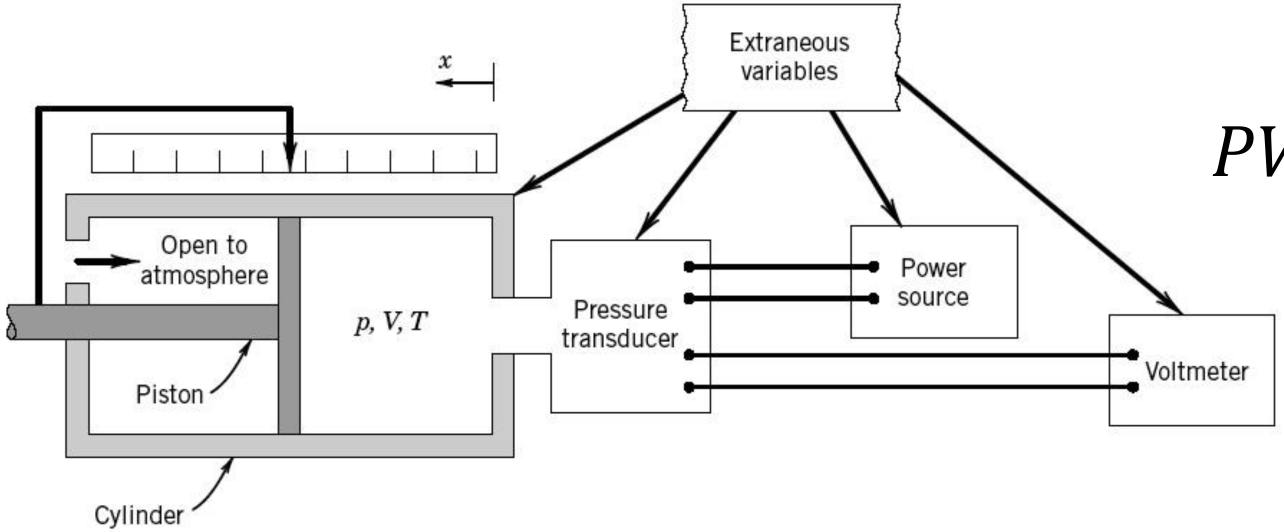
Dependent, independent and extraneous variables

$P=P(V,T,z_1,z_2,z_3)$

z1 =noise effect due to room temperature

z_2=line voltage

z_3 =connecting wires produce interference



$$PV = mRT$$

Figure 1.5 Pressure calibration system.

Example 1.2

Required: Randomize tests in example 1.1

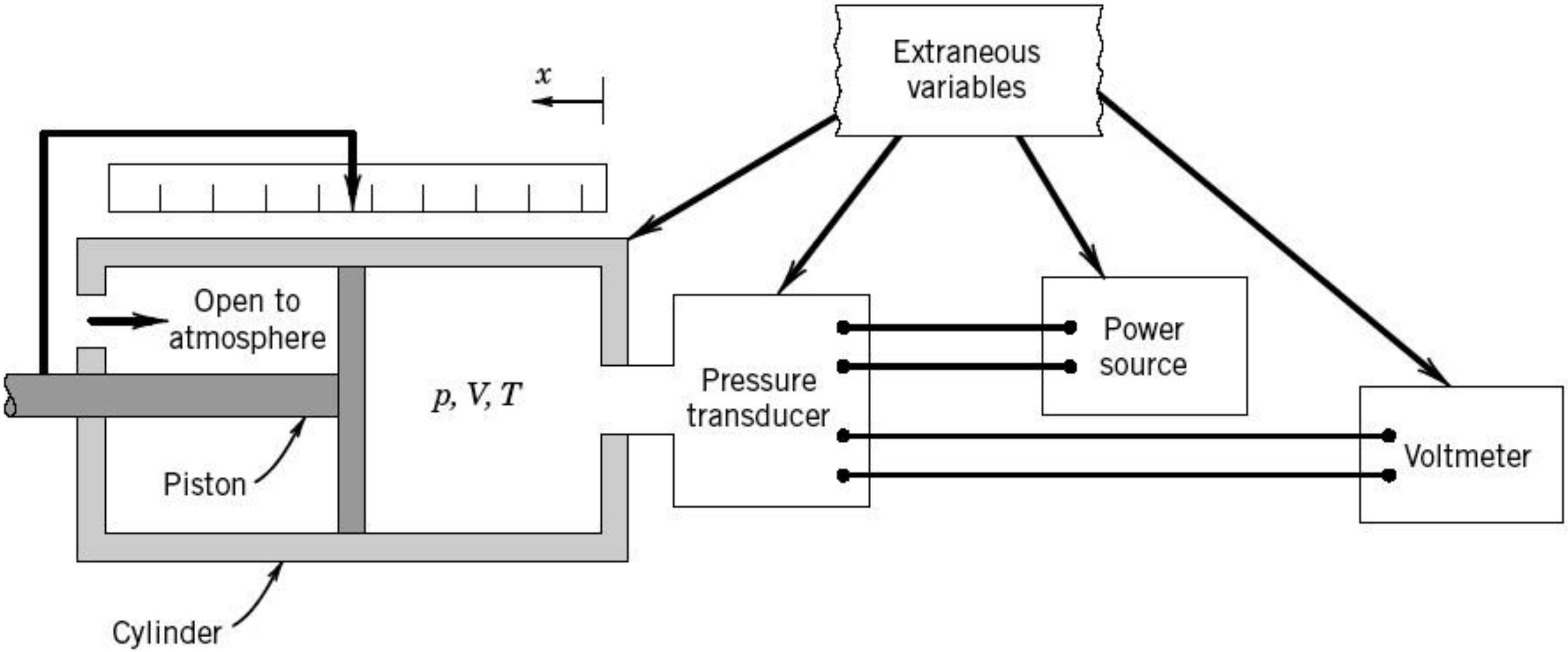


Figure 1.5 Pressure calibration system.

Example 1.2

since the extraneous variables are continuous, then shuffling the volume value (the independent variable) will randomize the test. Say do the testing with the following order for changing the volume V: V_2, V_5, V_1, V_4, V_6, V_3

Example 1.3 & 1.4

Random tests for discrete extraneous variables

Example 1.3

The strength of the mixture is function of binder-gel ratio and the operator. σ=f(binder, operator)

Required: test matrix to randomize the effect of the operator

Choose three different operators z_1, z_2, z_3. Each block with one operator

Block				
1	z_1	A	B	C
2	z_2	A	B	C
3	z_3	A	B	C

A, B, and C are different binder-gel ratio

Example 1.4

The strength of the mixture in example 1.3 is function of binder-gel ratio, temperature, and operator σ=f(binder, operator, T)

Required: suggest a random matrix testing

See the text book

Repetition & Replication

Repetition

Repeated measurements during **<u>single test run</u>** or a single batch. Operating conditions are held constant

Example: repeated measurements in factory of bearing diameter in a single batch

Repetition allows quantifying the variation of the measured variable i.e. finding the average and variance.

Replication

An independent duplication of the set of measurements using **<u>similar conditions,</u>**

Example: bearing diameter from day to day taking into account the operator, and may be the machine

Replication permits the assessment of how well we can **<u>duplicate</u>** a set of conditions

Example 1.5

Repetition and replication for room temperature

Repetition

Make measurements for room temperature to see how the temperature is maintained in the room [get average value, and the variation of T in the room]

Replication

Change the set-point temperature, bring it back to the same as the original value and then measure the room temperature (i.e. make another repetition i.e. duplicate). The two sets data are replication of each other

Concomitant methods

Obtain an estimate of the variable based on different methods as check and to make comparison

Example : Finding the volume of a cylinder

1-measure length and diameter, then find V

2-measure the weight and using the specific weight (i.e. density), calculate the volume

$$\rho = \frac{m}{V}$$

Calibration

Calibration is the process of applying a known input value to measurement system for the purpose of observing the output value. The known value used for calibration is called the **standard**

Calibration
- **Static (Time independent)**
- **Dynamic [Time dependent]**

Calibration

Static calibration: the input values are kept constant

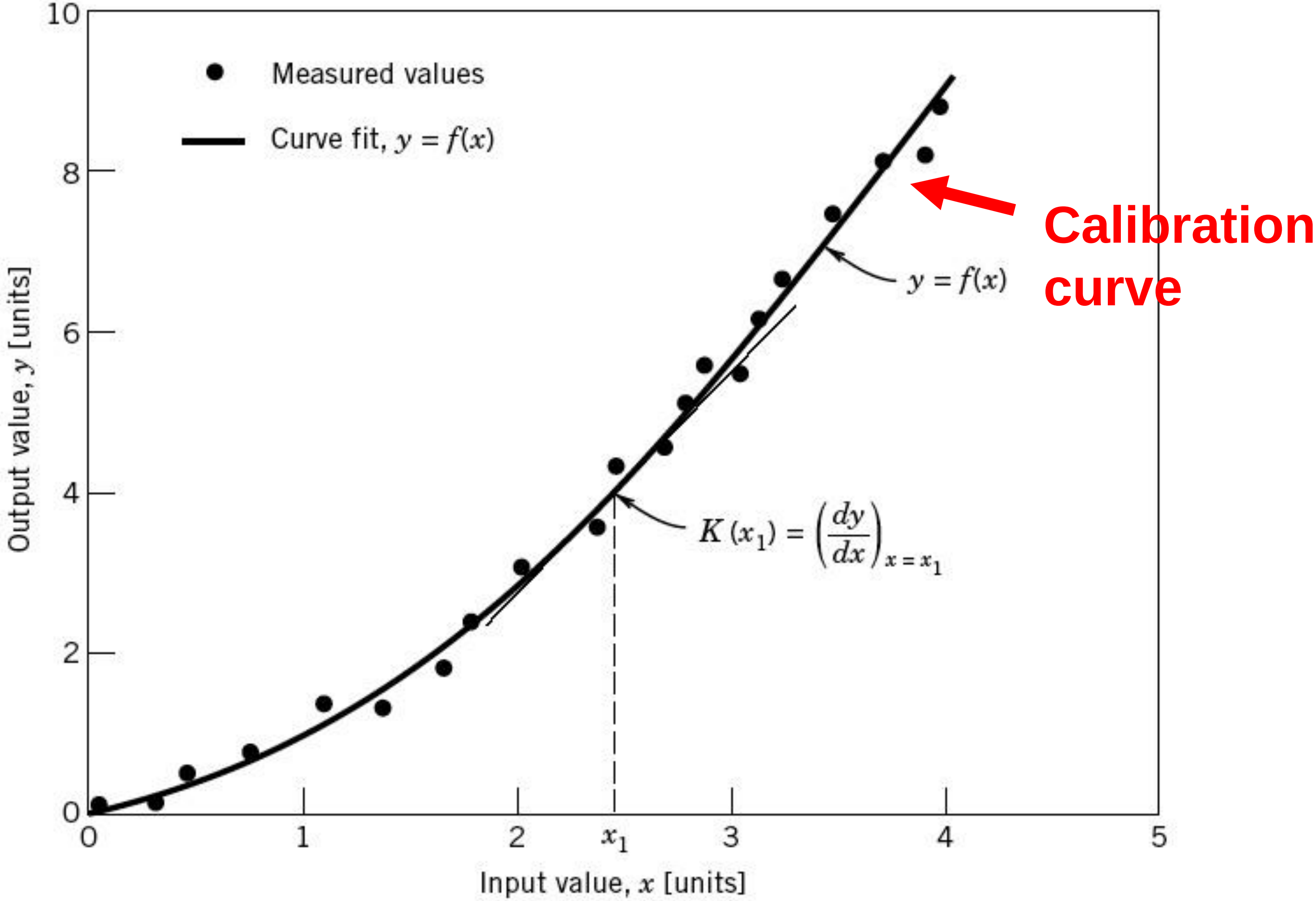


Figure 1.6 Representative static calibration curve.

Calibration

Dynamic Calibration

Input and output are time dependent.

Known input signals: step input, ramp input, sinusoidal signal

Example: variation of hot sphere temperature when exposed to sudden temperature drop

Calibration

Some Definitions

Static sensitivity K

$$K(x_1) = \left.\frac{dy}{dx}\right|_{x=x_1}$$

Input range or input span

$r_i = x_{max} - x_{min}$

Output range or output span

$r_o = y_{max} - y_{min}$

Full scale operating range =FSO=r_o

Calibration

Another form of the calibration curve

The difference of deviation between true or expected value y ' and indicated value y (i.e. y '-y) vs. y

Calibration

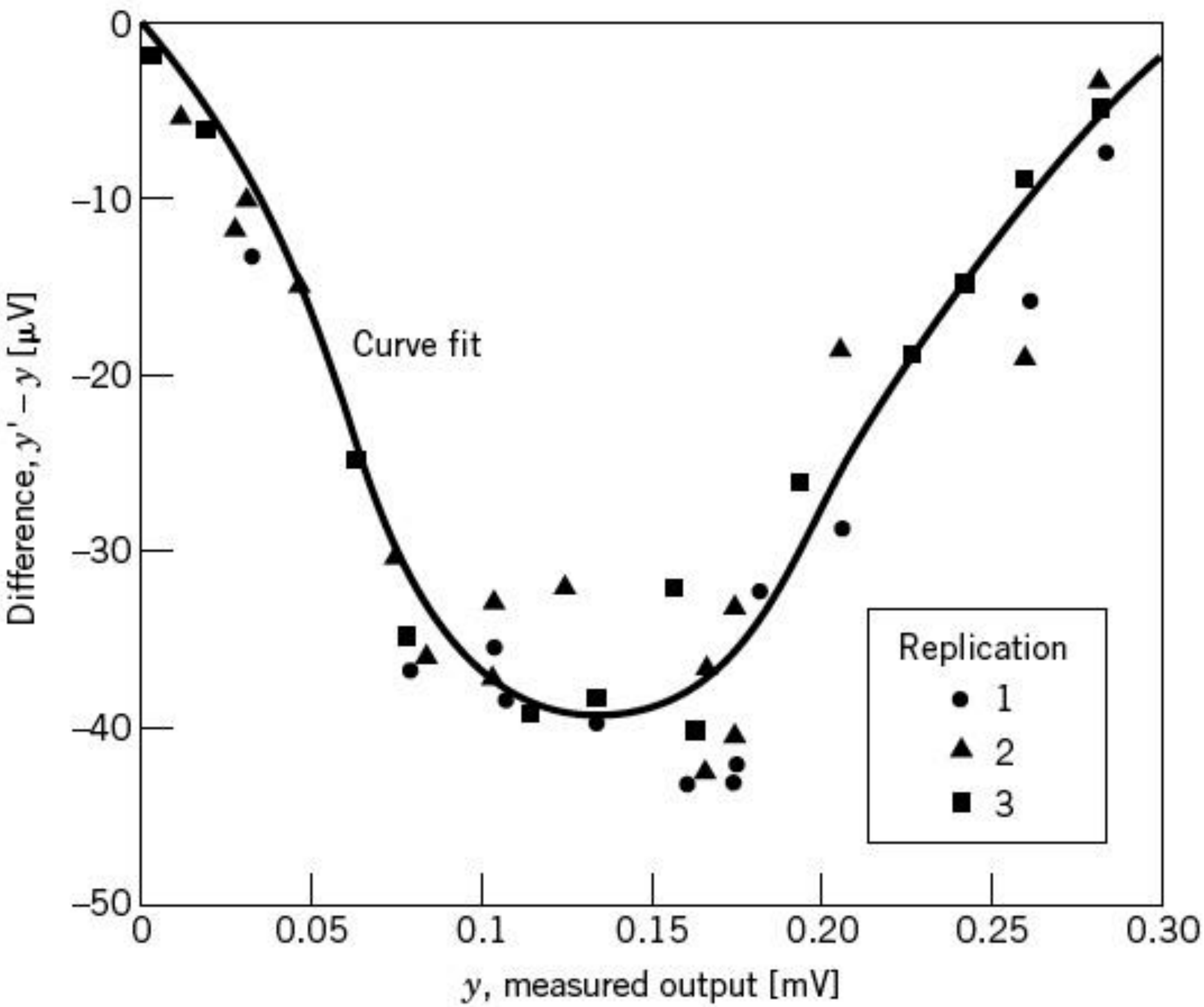


Figure 1.7 Calibration curve in the form of a deviation plot for a temperature sensor.

Error & Accuracy

Absolute error

ε=measured value-true value

Relative Accuracy

$$A = \left(\frac{|\varepsilon|}{true\ value} \right) * 100$$

Random error & Systematic error

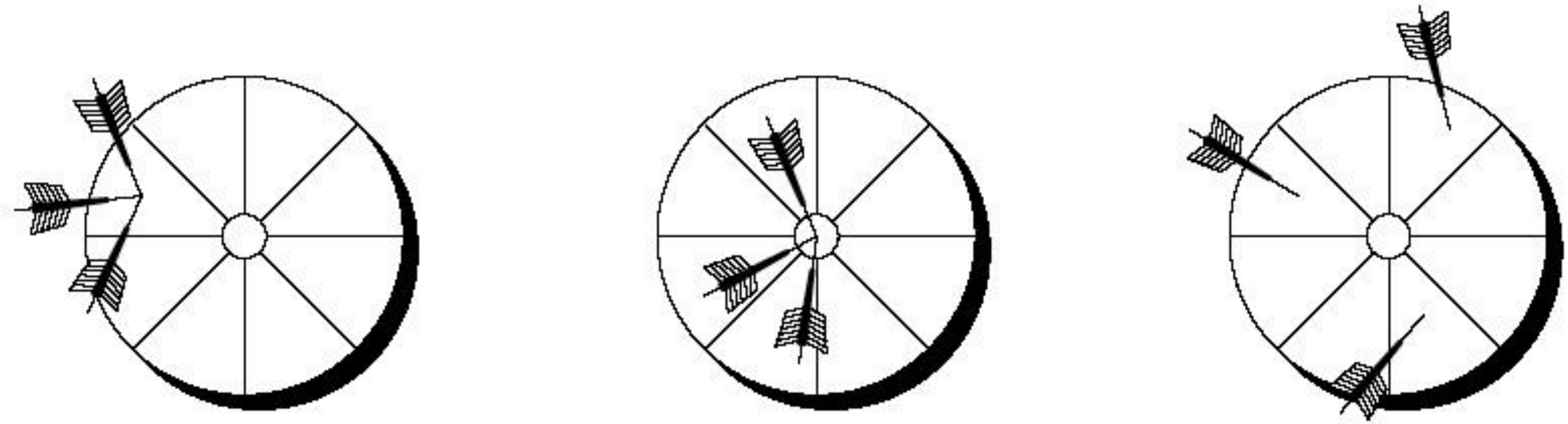
Random error or **Precision error**

When the measure value does not change over repeated same input. The measurement system is precise if it can produce the same output value for the same independent input. To know if a measurement system **precise** or not no need for **calibration**

Systematic error or Bias error or

If the indicated value is different than the true value. The measured value is said to contain systematic (bias) error. Systematic error is the difference between the average value and the true value

Random error & Systematic error



(*a*) High repeatability gives low random error but no direct indication of accuracy

(*b*) High accuracy means low random and systematic errors

(*b*) Systematic and random errors lead to poor accuracy

Figure 1.8 Throws of a dart: illustration of random and systematic errors and accuracy.

Low random error.
High Systematic error

Low random error.
Low systematic error

High random error.
High Systematic error

Random error & Systematic error

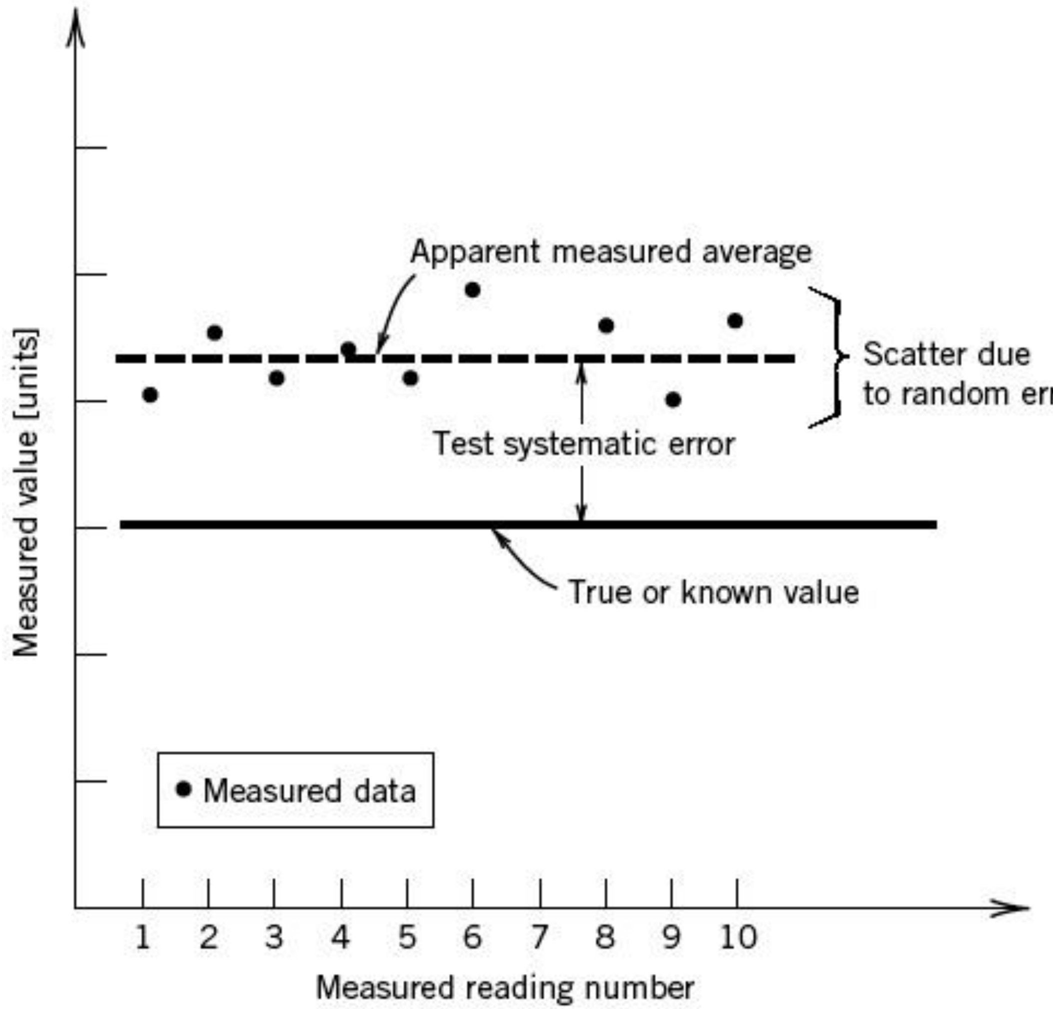


Figure 1.9 Effects of random and systematic errors on calibration readings.

Random error & Systematic error

High accuracy must imply both low systematic and random errors

Errors & uncertainty

- The magnitude of the error in any measurement can only be estimated
- Uncertainty is an estimation of the errors in the measured value
- Uncertainty results from errors that are present in the measurement system, calibration, and measurement technique, and is manifested by measurement system systematic and random errors

Definitions

Resolution

The smallest increment of the measured value that can be monitored

Sequential test

Applying sequential variation of the input either upscale or down scale

Hysteresis error, e_h

Error due to the difference when doing the test in upscale sequential test and down scale sequential test.

$$e_h = y_{upscale} - y_{downscale}$$

$$\%e_{h,\max} = \frac{e_h}{r_o} * 100$$

Random test

Random variation of the input to reduce hysteresis errors

Definitions

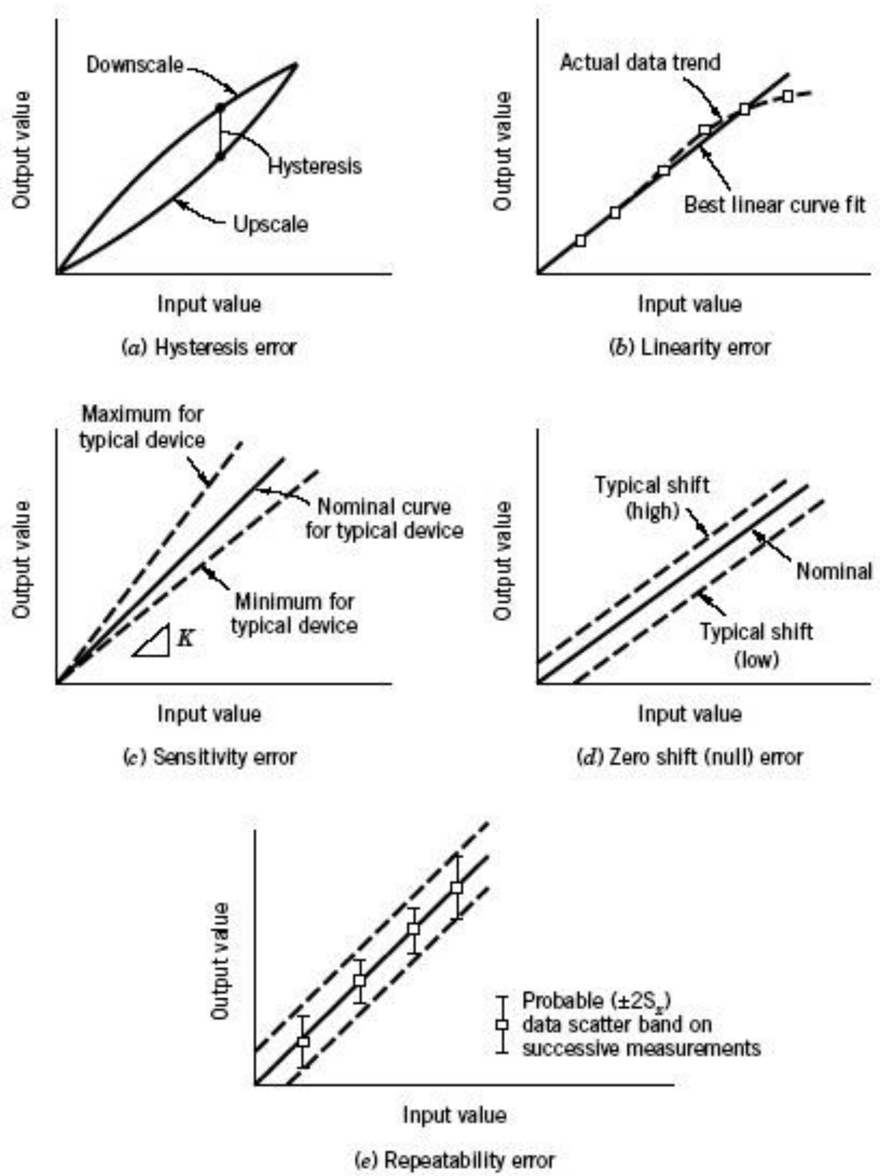


Figure 1.10 Examples of some common elements of instrument error. (*a*) Hysteresis error. (*b*) Linearity error. (*c*) Sensitivity error. (*d*) Zero shift (null) error. (*e*) Repeatability error.

Common Instrument Errors

Hysteresis error
Linearity error
Sensitivity error
Zero shift error
Repeatability error

Definitions

Linearity error e_L

For linear relationship between the input and the output

$y_L = a_0 + a_1 x$ **The linear error** $e_L = y - y_L$

$$\%e_{L\max} = \frac{e_{L,\max}}{r_o} * 100$$

Sensitivity error, e_K

Is the statistical measure of the random estimate of the slope of calibration curve

Zero error, e_z

Occurs when the zero intercept is not fixed, but the sensitivity is constant

Definitions

Instrument repeatability

The ability of the instrument to indicate the same value upon repeated but independent application of the same input. Base on replication tests on the lab. Statistically measured.

If S_x is the standard of deviation, then

$$\%e_{R\max} = \frac{2S_x}{r_o} * 100$$

Reproducibility

Closeness of the agreement obtain from duplicate tests carried out under **changed conditions** of the measurements. Test performed in different labs.

Definitions

Instrument precision

Some manufacturers use this term to mean random error

Overall instrument error

$$u_c = \left[e_1{}^2 + e_2{}^2 + e_3{}^2 .... + e_m{}^2\right]^{1/2}$$

u_c is called instrument uncertainty

Definitions

Table 1.1 Manufacturer's Specifications: Typical Pressure Transducer

Operation	
Input range	0–1000 cm H_2O
Excitation	±15 V dc
Output range	0–5 V
Performance	
Linearity error	±0.5% FSO
Hysteresis error	Less than ±0.15% FSO
Sensitivity error	±0.25% of reading
Thermal sensitivity error	±0.02% /°C of reading
Thermal zero drift	±0.02% /°C FSO
Temperature range	0–50 °C

Standards units

Calibration must be done against standard

Basic SI units

Parameter	**SI unit**
Length	m
Mass	kg
Time	s
Amount of substance	mole
Temperature	K
Current	Ampere
Luminous intensity	Candela

Standards units

International agreement to use SI units

Example of basic primary SI units

1 kg

The mass of particular platinum-iridium cylindrical bar that is maintained at specific condition, in France

A new definition of kg was approved Nov. 2018 based on Planck's constant using **Kibble force balance**

1 second

Time elapsed during 9,192,631,770 periods of the radiation emitted between excitation levels of the fundamental state of cesium 123

Other basic SI units are also defined such as K for temperature, m (for length), and Ampere (for current)

Primary and derived units

Table 1.2 Dimensions and Units*

	Dimension	
Unit	SI	IP
Primary		
Length	meter (m)	inch (in)
Mass	kilogram (kg)	pound-mass (lb_m)
Time	second (s)	second (s)
Temperature	kelvin (K)	rankine (°R)
Current	ampere (A)	ampere (A)
Substance	mole (mol)	mole (mol)
Light intensity	candela (cd)	candela (cd)
Derived		
Force	newton (N)	pound-force (lb)
Voltage	volt (V)	volt (V)
Resistance	ohm (Ω)	ohm (Ω)
Capacitance	farad (F)	farad (F)
Inductance	henry (H)	henry (H)
Stress, Pressure	pascal (Pa)	pound-force/inch^2 (psi)
Energy	joule (J)	British thermal unit (BTU)
Power	watt (W)	foot pound-force (ft-lb)

*SI dimensions and units are the international standards. IP units are presented for convenience.

Standard tests and codes

Very well-known societies and organization issue test standards and codes. For example

ASME issue standards for testing **gas turbine** for example

ASHRAE issue standards for testing **fans** for example

ISO issue standards for testing **window type air conditioner**

And so forth for other organizations such as

NIST=National Institute of standards and testing

ARI=American Refrigeration Institute

SMACNA=Sheet Metal Air Conditioning National Association

TEMA=Tubular Exchanger Manufacturer Association (www.tema.org)

The Saudi Standards, Metrology and Quality Organization (SASO) https://saso.gov.sa

Example

Testing of window type air conditioning and determining the COP or EER (Energy efficiency ratio)

Hierarchy of Standards

Table 1.3 Hierarchy of Standards[*]

Primary Standard	Maintained as Absolute Unit Standard
Transfer Standard	Used to calibrate Local Standards
Local Standard	Used to calibrate Working Standards
Working Standard	Used to calibrate local instruments

[*] There may be additional intermediate standards between each hierarchy level.

Hierarchy of Standards

Example: Temperature measurement standards

Table 1.4 Example of a Temperature Standard Traceability

Standard		
Level	Method	Error [°C]*
Primary	Fixed thermodynamic points	0
Transfer	Platinum resistance thermometer	± 0.005
Working	Platinum resistance thermometer	± 0.05
Local	Thermocouple	± 0.5

* Typical instrument systematic and random errors.

Data Presentation

Rectangular scale, (example $y=a+bx$)

Semi-log scale, example ($y=ae^{bx}$)

Log- log scale (example $y=ax^b$)

Learn how to use Trendline in Excel program

Data Presentation

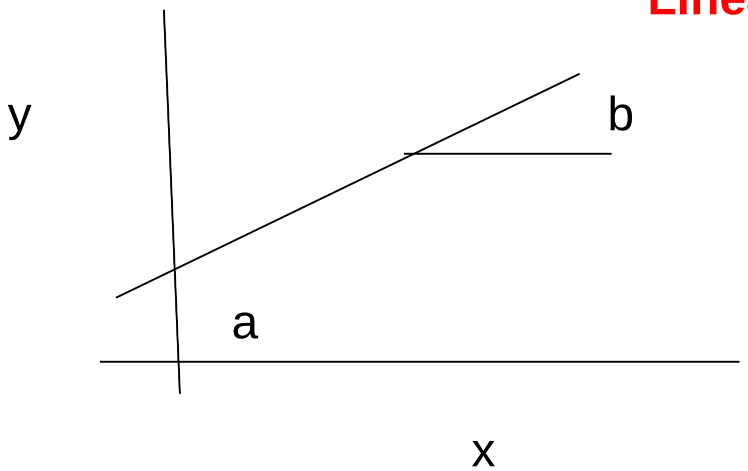
1-Linear relation

$$y = a + bx$$

$$b = \frac{y_2 - y_1}{x_2 - x_1} \qquad a = y_3 - bx_3$$

a and b can be found directly from figure.

Linear paper



2- Exponential relation

$$y = ae^{bx}$$

$$\log(y) = \log(a) + bx\log(e)$$

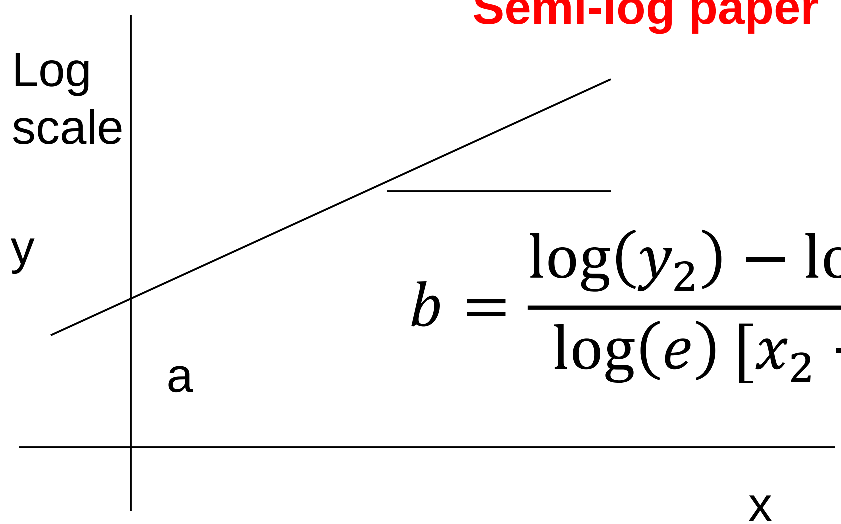
$$Y = A + b * cx$$

or

$$\ln(y) = \ln(a) + bx$$

$$b = \frac{\ln(y_2) - \ln(y_1)}{x_2 - x_1}$$

Semi-log paper

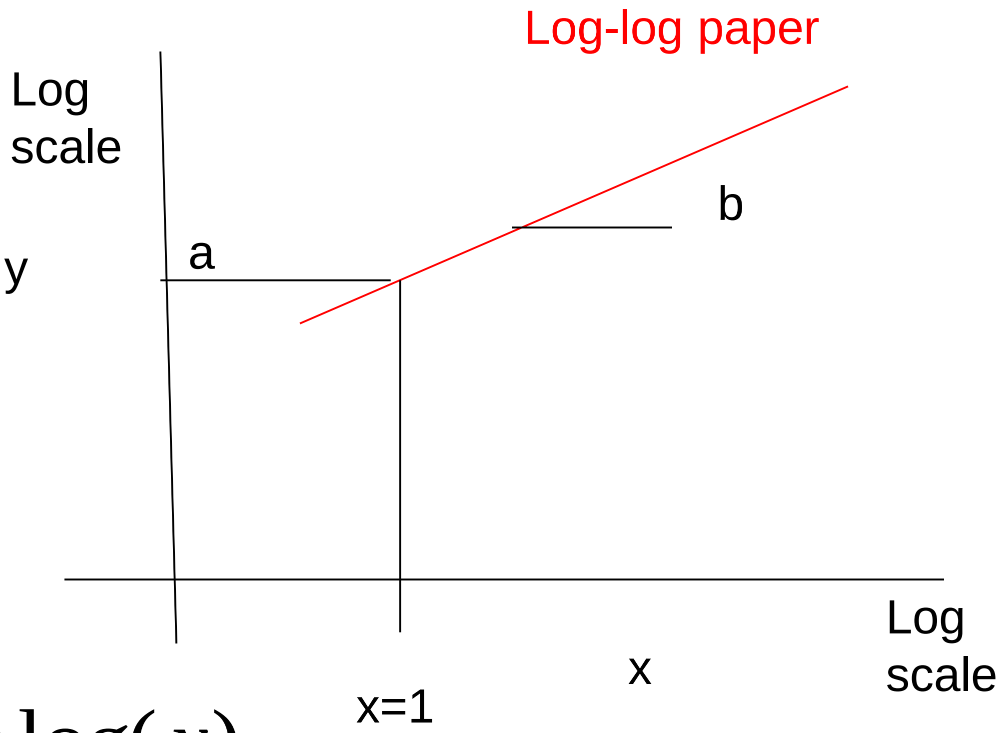


$$b = \frac{\log(y_2) - \log(y_1)}{\log(e)\,[x_2 - x_1]}$$

Data Presentation

3-Power relation

$$y = ax^b$$



$$\log(y) = \log(a) + b\log(x)$$

$$Y = A + bX$$

$$b = \frac{\log(y_2) - \log(y_1)}{\log(x_2) - \log(x_1)}$$

At x=1, one can get the intercept A, but since the scale is logarithmic, then it is the value a

a can be found directly from the figure.

Significant figures or digits

The number of digits that are relevant and meaningful

For engineering Applications use of 3 significant figures, such as 12.3 or 123. 0.0123

In order to determine the number of significant digits, write the number in exponent format and follow the significant digit rules

Significant figures or digits

Rules for significant figures

1-Non zero digits are always significant [Ex. 29.7 $\rightarrow$ 3SF]
2-Any zeros between significant digits are significant [Ex. 400.3 $\rightarrow$ 4SF]
3-A final zero or trailing zeros of a decimal portion are significant [Ex. 4.0000 $\rightarrow$ 5SF]
4-Integer number are with infinite significant figures [Ex. 3 $\rightarrow$ infinite SF]
5-Leading zeros are not counted.
[Ex. 0.0056 $\rightarrow 5.6*10^{-3} \rightarrow$ 2SF]

Significant digits

Number	Exponential form	Significant digits	Remarks
12.3	$1.23*10^{1}$	3	No zeros, all digits are significant
123,000.	$1.23000*10^{5}$	6	Zeros in the middle are counted
0.00123	$1.23*10^{-3}$	3	Leading zeros are not counted
40,300.	$4.0300*10^{4}$	5	Zeros in the middle are counted
0.005600	$5.600*10^{-3}$	4	Trailing zeros are counted
0.0056	$5.6*10^{-3}$	2	Leading zeros not counted
0.006	$6.*10^{-3}$	1	Leading zeros not counted
123	$1.23*10^{3}$	infinite	integer
123,000	$1.23*10^{5}$	3	Large number (number in thousands). No decimal point

Significant digits

When multiplying two number having different significant figures, the resulted number must be written with the smallest number of significant figures of either of the two numbers

For engineering calculations keep 3 significant figures

Example A=2.3601, B=0.34

$A=2.3601*10^{1}$ [5 SF], $B=3.4*10^{-1}$ [2 SF]

AB=2.3601*0.34=0.802434

AB=0.80 [2 SF]

Significant digits

Adding and subtracting rule for significant figures

1-Align the numbers so that the decimal point be on the top of each other
2-Find the number that has the least number of places after the decimal point
3-Round your results to the last number of places found in 2

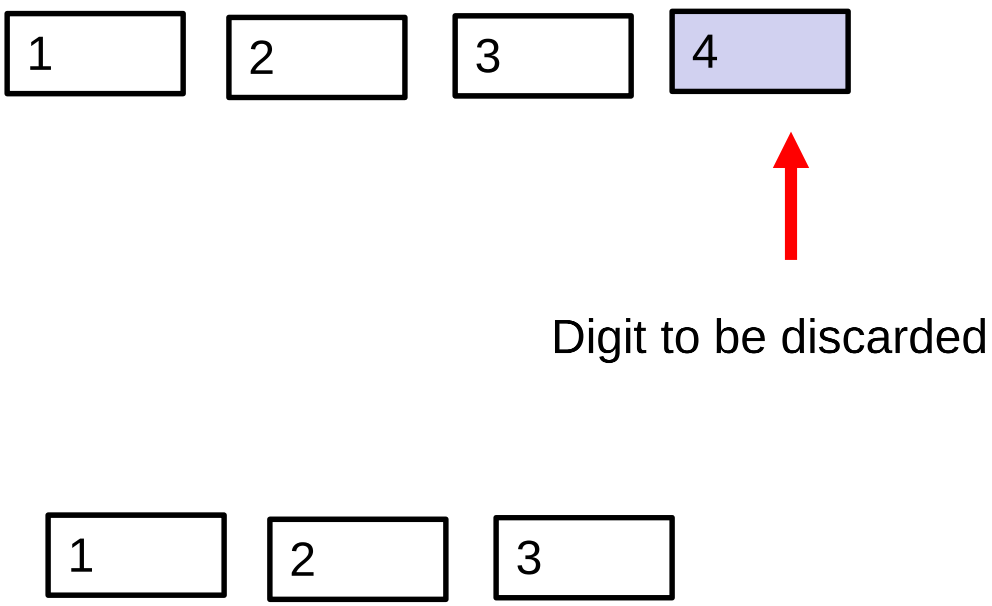
Example

Add 3.461728 and 14.91

$$\begin{array}{r} 3.461728 \\ 14.91 \\ \hline 17.37 \end{array}$$

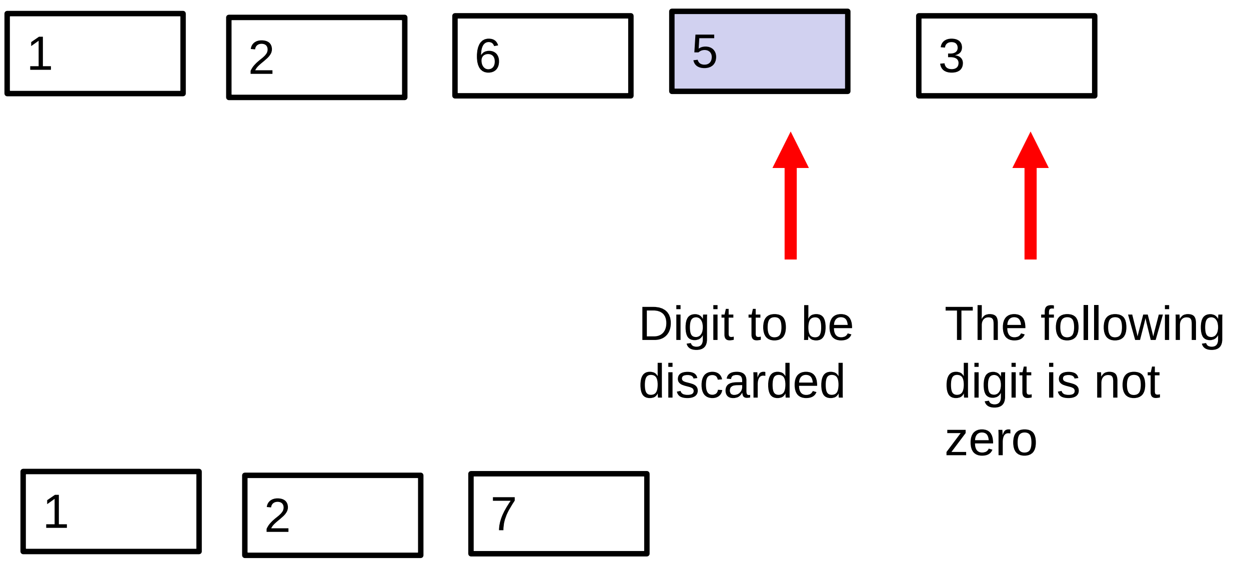
Rounding the resulted numbers

- 1-If the digits to be discarded begin with a digit less then 5, the preceding number is not changed.



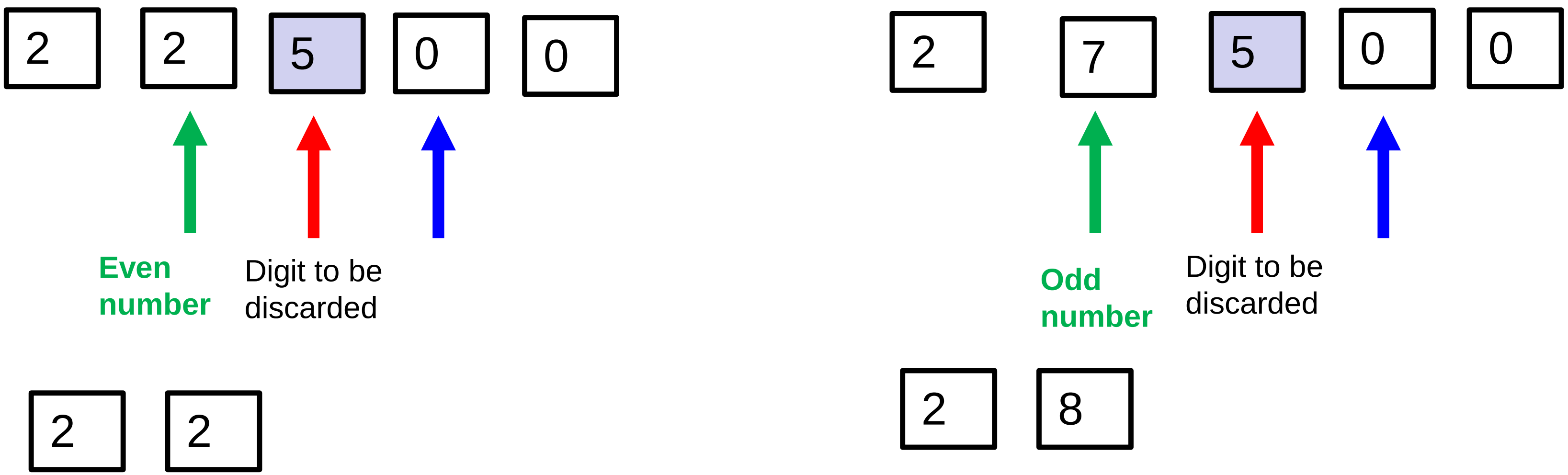
Rounding the resulted numbers

- 2-If the digits to be discarded begins with a 5 and at least one of the following digits is greater than 0, the digit preceding the 5 is increased by 1



Rounding the resulted numbers

3-If the digits to be discarded begin with a 5 and all the following digits are 0, the digit preceding the 5 is unchanged if it is an even number and increased by 1 if it is an odd number



Rounding the resulted numbers

- 4-The number of significant digits is an exact count is not considered when establishing the number of significant figure digit to be reported

- 5-Round your final result but do not round the intermediate calculations

Example 1.12

A handheld appliance consumes 1.41 kW of power. So two identical units (exact count $N = 2$) consume $1.41\ \text{kW} \times 2 = 2.82\ \text{kW}$ of power. The exact count does not affect the significant digits in the result.

Rounding the resulted numbers

Example 1.11

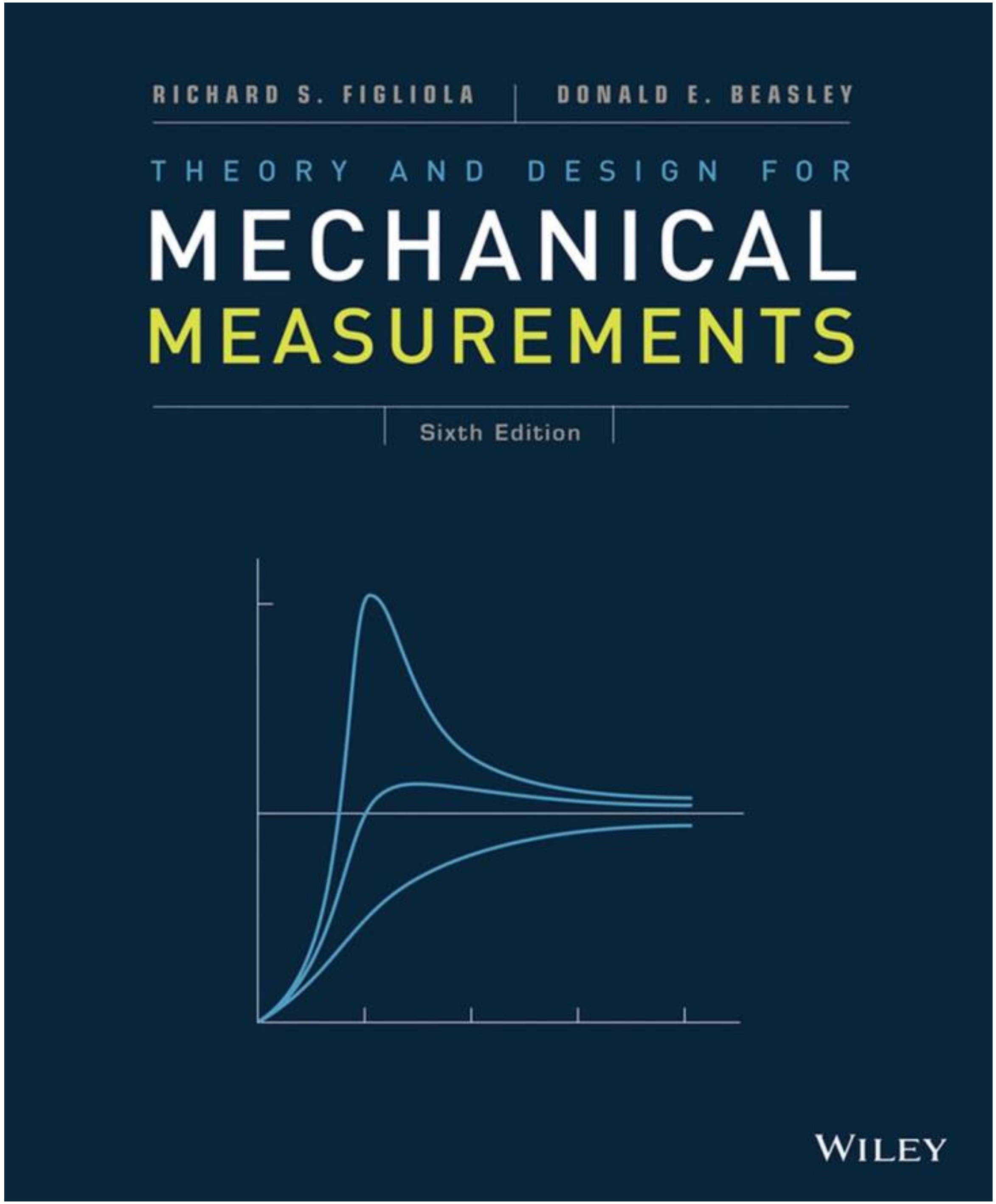
Round the following numbers to three significant digits and then write them in scientific notation.

49.0749	becomes	49.1 or 4.91×10^1
0.0031351	becomes	0.00314 or 3.14×10^{-3}
0.0031250	becomes	0.00312 or 3.12×10^{-3}

Youtube channel

Sample of students’ project

https://www.youtube.com/channel/UClNDEzQAXIGqIKhf0SPVj4A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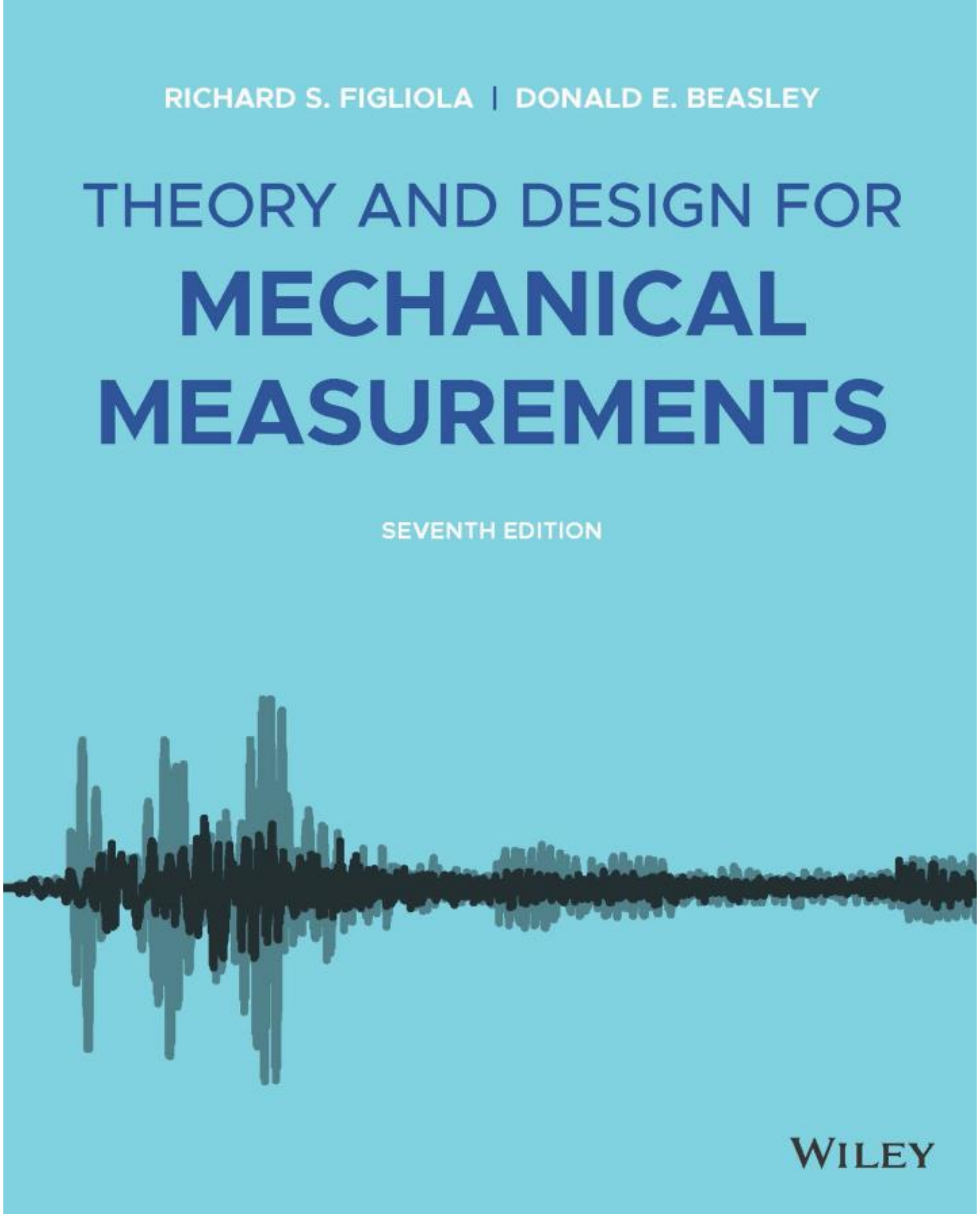
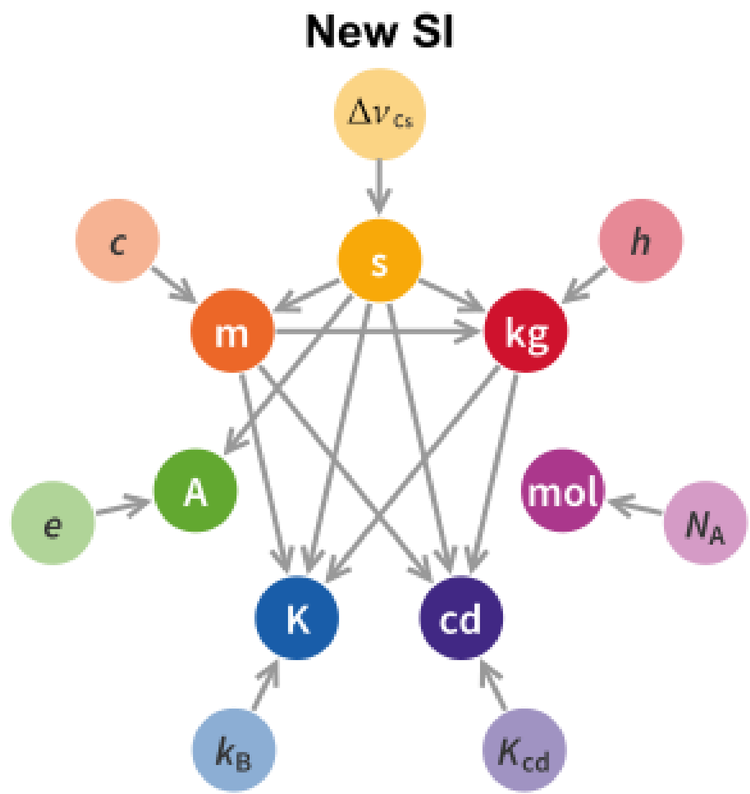

RICHARD S. FIGLIOLA | DONALD E. BEASLEY
THEORY AND DESIGN FOR
MECHANICAL
MEASUREMENTS
SEVENTH EDITION
WILEY



New definition of kg based on Planck constant

A **Kibble balance** (previously, **watt balance**) is an electromechanical measuring instrument that measures the weight of a test object very precisely by the strength of the electric current and voltage needed to produce a compensating force.

English term or word	**المعنى بالعربية**	
sensor	مجس	
transducer	مستشعر	
Signal conditioning	تهيئة الاشارة	
Noise	تشويش او ازعاج	
Interference	تداخل	
calibration	معايرة	
variables	المتغيرات	
Dependent	تعتمد على غيرها	
independent	لا تعتمد على غيرها	
Extraneous variable	متغير متعد	
Sequential test	اختبار متسلسل	
Random test	اختبار عشوائي	

English term or word	**المعنى بالعربية**	
hysteresis	التخلف	
Uncertainty	درجة الشك	
Calibration curve	منحنى المعايرة	
Sensitivity	الحساسية	
RSS root sum of squares	مجموع المربعات تحت الجذر	
Input range	مدى المدخل	
Output range	مدى المخرج	
Accuracy	صحة القراءة	
precision	دقة القراءة	
Random error	الخطا المبعثر او العشوائي	
Bias or precision error	الخطأ المنتظم، المتحيز،	

English term or word	**المعنى بالعربية**	
Resolution	التفصيل	
Significant figures	الارقام المعنوية	
repetition	تكرار	
replication (duplication)	تناسخ	

Precision and Accuracy

- Precision is a measure of consistency or repeatability. For instance, my bathroom scale is not properly zeroed so that it consistently reads too low by 4.5 to 4.6 lbs. This scale is precise.

- Accuracy is a measure of the error in a reading or measurement. The scale in the above example is not accurate. If, on the other hand, the scale sometimes was too high and sometimes too low it may be considered accurate in the average… but not precise.

Sep. 2019

Important for plotting function on rectangular, smilog or log log scales

In log linear graph for an exponential relation such as y=a exp(bx)

You get a linear line on such semilog plot
But you can not get the slope because one can use different distances for x and y scales
You can get the value of b as follows

b=(log(y2-log(y1)/[(log(e*(x2-x1)]
or
use ln function
b= ln(y2)-ln(y1)/(x2-x1)

you can get a value by looking at the figure when x=1

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for log log scale you can find a and b from the figure provided that the distances for in x and y log scales are the same